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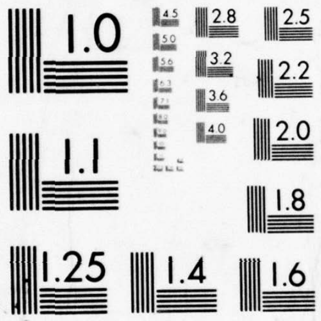
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A GENEALOGY OF CONTROL STRUCTURES

by

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ABSTRACT

The issue of control structures has had a heated history in programming. To put this issue on a solid footing, this paper reviews numerous theoretical results on control structures and explores their practical implications.

The classic result of Bohm and Jacopini on the theoretical completeness of if-then-else and while-do is discussed. Several recent ideas on control structures are then explored. These include a review of various other control structures, results on time/space limitations, and theorems relating the relative power of control structures under several notions of equivalence.

In conclusion, a case is made against the recent arguments of Knuth [K2] on the utility of the GOTO statement.

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The issue of control structures has had a heated history in programming. To put this issue on a solid footing, this paper reviews numerous theoretical results on control structures and explores their practical implications. The classic result of Bohm and Jacopini on the theoretical completeness of if-then-else and while-do is discussed. Several recent ideas on control structures, results on time/space limitations, and theorems relating the relative power of control structures under several notions of equivalence. In conclusion, a case is made against the recent arguments of Knuth (K2) on the utility of the GOTO statement.

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I. INTRODUCTION

In the last decade we have seen the rapidly growing interest in the areas of structured programming and software quality. Although the major attention has been placed on top-down programming techniques and control structures, the concern over the quality of software has also included the definition, modularity, clarity, changeability, and documentation of programs.

This paper focuses on the issue of control strucures. While it may well be argued that the control structure issue has been entirely overworked, the debates and polarized opinions remain. At one extreme we have the views of Mills [M1], who has religiously advocated the use of the <u>if</u>-<u>then</u>-<u>else</u> and <u>while</u>-<u>do</u> control structures. At the other extreme, we have the views of Knuth [K2], who has recently given vigorous arguments on the utility of the <u>goto</u>.

Over the years, a number of theoretical results have been presented on the limitations of variou3 control structures. Notable are the works of Bohm and Jacopini [B1, M1], Knuth and Floyd [K3], Bruno and Steiglitz [B2], Peterson, Kasami and Tokura [P1], and importantly, Kosarju [K4]. These results have placed the control structure issue on a firm foundation. In this paper I present a framework for reviewing these results and discuss their practical implications.

The programming language PASCAL is used here as communication language. Unfortunately, PASCAL omits several constructs that I consider important in contemporary languages. To remedy this situation, I have made a number of extensions, as required by the examples. I believe that these extensions will pose little problem for the reader.

II. CLASSES OF CONTROL STRUCTURES

This section presents various classes of control structures. Aside from minor variants, these classes embrace the control structures found in most algorithmic languages. Readers who are familiar with these control structures may need only a quick reading of this section to become familiar with the terminology given here.

(a) D-structures. We begin with the definition of "D-structures", D for Dijkstra, as in [B2]. A D-structure (see Figure 1) is any program constructed only from the following 1-in, 1-out primitive structures

(i) basic actions (e.g., assignment statements, procedure calls, input/output statements),

(ii) compositions "$s_1;s_2$" of two D-structures,

(iii) conditional constructs of the form "if p then s_1 else s_2" based on a predicate p (having no side effects) and two D-structures s_1 and s_2, and

(iv) loops of the form "while p do s", where p is a predicate (having no side-effects) and s is a D-structure.

D-structures also include conventional for loop structures. These can be readily defined via basic actions and while-do loops.

D-structures have received prominent attention in the literature. Bruno and Steiglitz [B2], Ashcroft and Manna [A1], and Knuth and Floyd [K3] have explored the reduction of arbitrarily structured programs into D-structure form. Mills [M1] and Dijkstra [D2] have explored programming with these structures, and numerous other researchers [F1,H1,L1,W3] have considered these structures in various ways.

(b) D'-structures. The class of D-structures gives rise to several natural extensions. One class of control structures, here called D'-structures, is shown in Figure 2. This class comprises the class of D-structures, with the addition of the following 1-in, 1-out structures: single branching if statements, n-way branching case statements, and repeat-until loops.

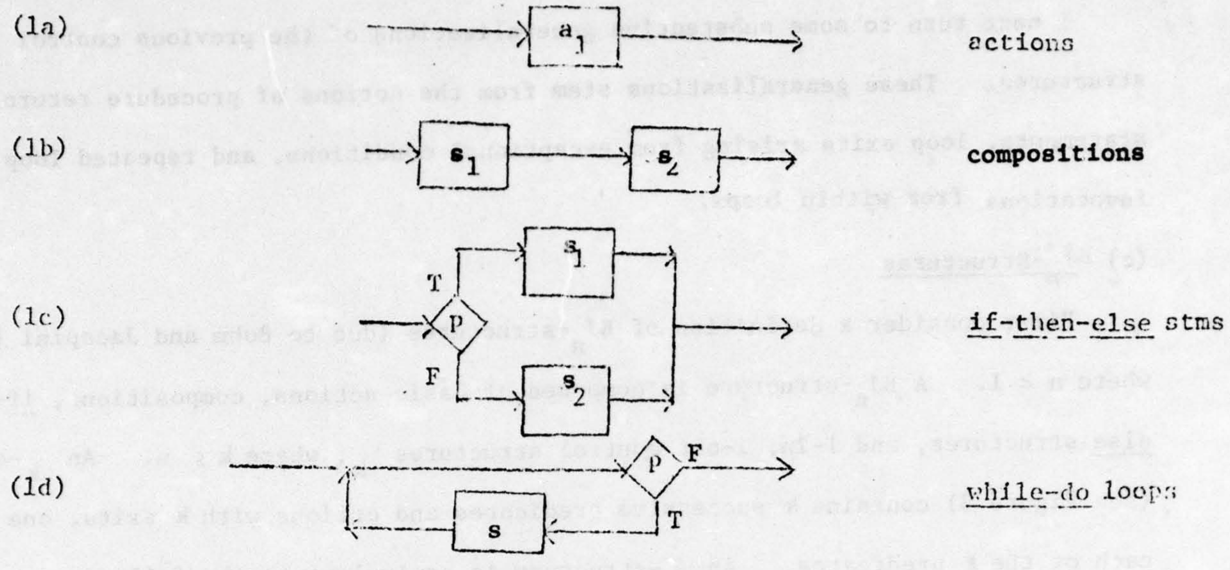

Figure (1) **Definition of D-structures**

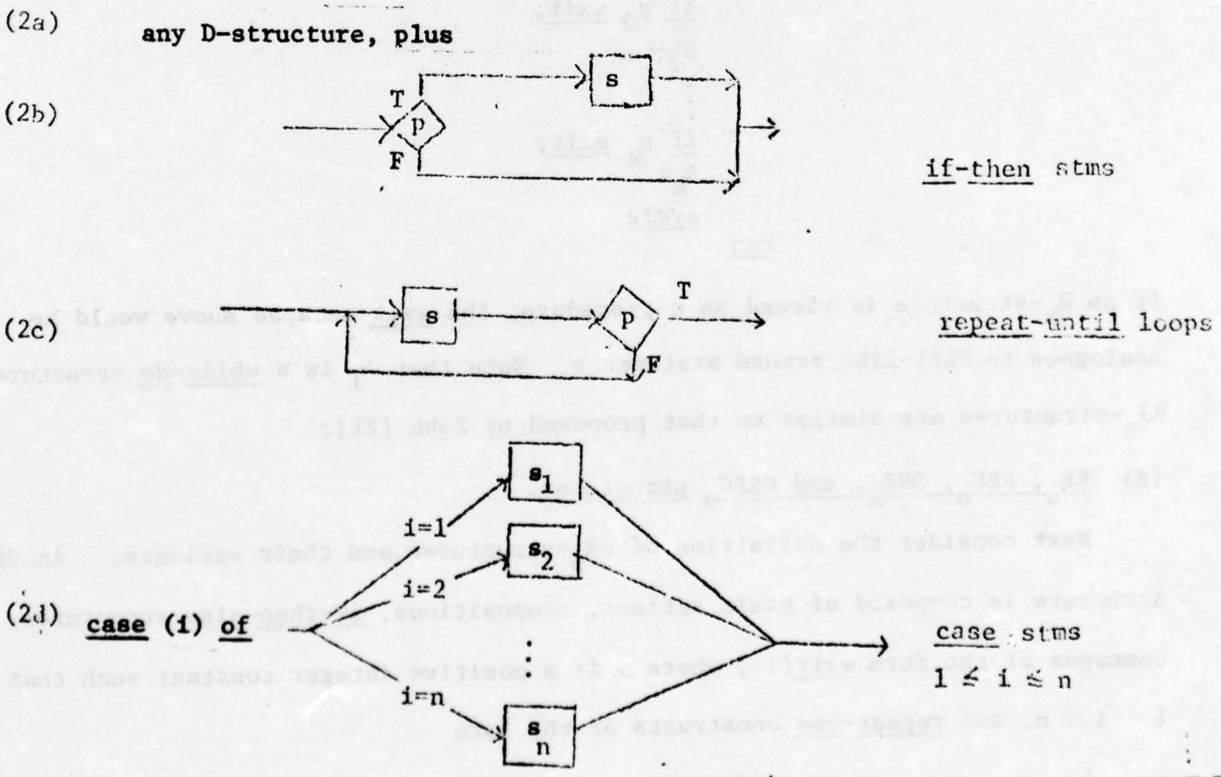

Figure (2) **Definition of D'-structures**

Aside from the goto, D'-structures comprise the set of PASCAL control structures.

I next turn to some substantive generalizations of the previous control structures. These generalizations stem from the notions of procedure return statements, loop exits arising from exceptional conditions, and repeated loop invocations from within loops.

(c) BJ_n-Structures

First consider a definition of BJ_n-structures (due to Bohm and Jacopini [B1]), where $n \geq 1$. A BJ_n-structure is composed of basic actions, compositions, if-then-else structures, and 1-in, 1-out control structures Ω_k, where $k \leq n$. An Ω_k-structure (see Figure 3) contains k successive predicates and actions with k exits, one for each of the k predicates. An Ω_k-structure is equivalent to the following program schema.

```
do  if $p_1$ exit;
    $s_1$;
    if $p_2$ exit;
    $s_2$;
    :
    if $p_k$ exit;
    $s_k$;
    cycle
end
```

If an Ω_k-structure is viewed as a procedure, the exit escapes above would be analogous to PL/I-like return statements. Note that Ω_1 is a while-do structure. BJ_n-structures are similar to that proposed by Zahn [Z1].

(d) RE_n, REC_n, DRE_n, and $DREC_n$ Structures.

Next consider the definition of RE_n-structures.and their variants. An RE_n-structure is composed of basic actions, compositions, if-then-else structures, exit commands of the form exit(i), where i is a positive integer constant such that $1 \leq i \leq n$, and repeat-end constructs of the form

```
repeat
    $s_1$;
    $s_2$;
    :
    $s_n$
end
```

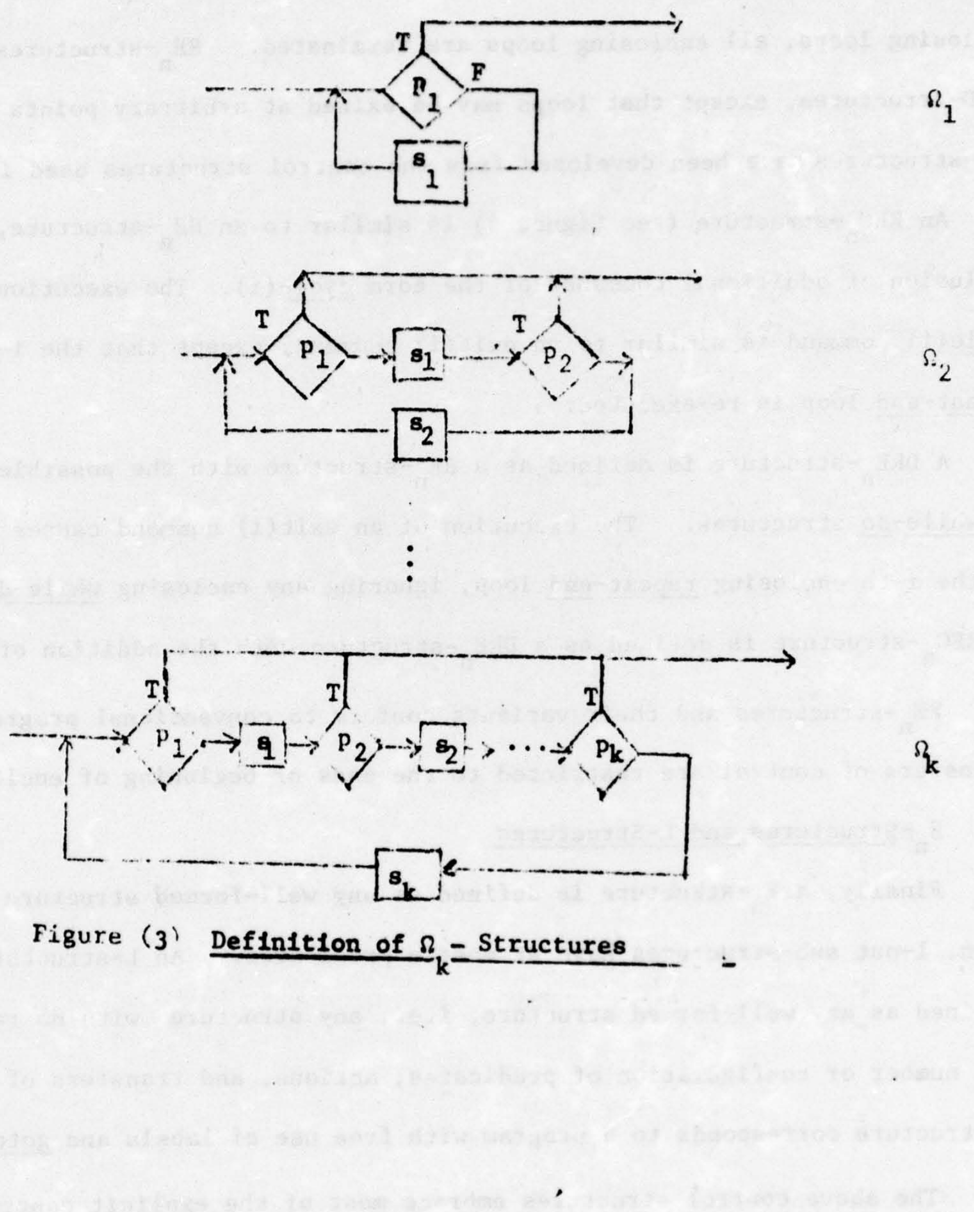

Figure (3) **Definition of Ω_k - Structures** where the s_i are other RE_n-structures (see Figure 4). On execution, the commands within a repeat-end block are to be repeated indefinitely until an exit command is encountered. The execution of an exit(i) command causes termination of i enclosing repeat-end loops. In the case where there are fewer than i enclosing loops, all enclosing loops are terminated. RE_n-structures are similar to D-structures, except that loops may be exited at arbitrary points within the loop. RE_n-structures have been developed from the control structures used in BLISS[W4].

An REC_n-structure (see Figure 5) is similar to an RE_n-structure, with the inclusion of additional commands of the form cycle(i). The execution of a cycle(i) command is similar to an exit(i) command, except that the i-th enclosing repeat-end loop is re-executed.

A DRE_n-structure is defined as a RE_n-structure with the possible inclusion of while-do structures. The execution of an exit(i) command causes termination of the i-th enclosing repeat-end loop, ignoring any enclosing while-do loops. A $DREC_n$-structure is defined as a DRE_n-structure with the addition of cycle(i) command.

RE_n-structures and their variants conform to conventional programs for which transfers of control are restricted to the ends or beginning of enclosing control loops.

(e) P_n-Structures and L-Structures

Finally, a P_n-structure is defined as any well-formed structure such that all 1-in, 1-out sub-structures have at most n predicates. An L-structure is defined as any well-formed structure, i.e., any structure with no restrictions on the number or configuration of predicates, actions, and transfers of control. An L-structure corresponds to a program with free use of labels and goto statements.

The above control structures embrace most of the explicit control structures found in conventional languages. It is important to note that these control structures do not take into account various "scope" rules often associated with these control structures. In PASCAL for example, the value of a for-loop control variable upon exit is undefined. Such issues arising from the value of internal variables when control is transferred into or out of a control loop are not treated in this paper.

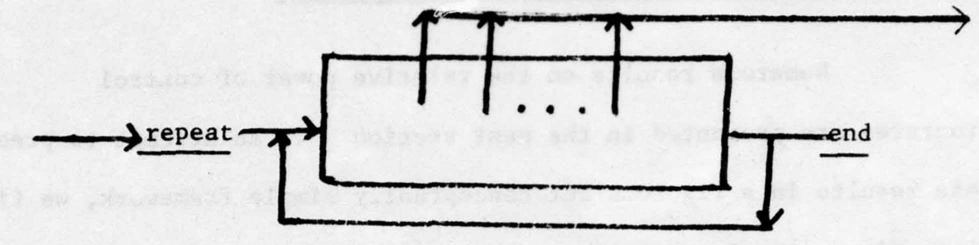

Figure (4) <u>Repeat-exit</u> Structures

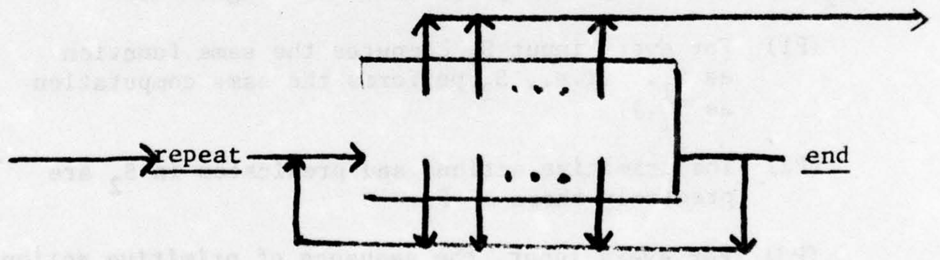

Figure (5) <u>Repeat-exit-cycle</u> Structures

III. THE NOTIONS OF REDUCIBILITY AND EQUIVALENCE

Numerous results on the relative power of control structures are presented in the next section. In an attempt to present these results in a rigorous but conceptually simple framework, we first define five sets of conversion rules for converting a control structure into another form, and then introduce the notions of "reducability" and "equivalence" of classes of control structures under these conversion rules. These notions are motivated by Kosaraju [K4].

3.1 Conversion rules

In defining the various notions of conversion of a structure S_1 to a structure S_2, the following five properties are singled out:

(P1) For every input S_2 computes the same function as S_1. (i.e., S_2 performs the same computation as S_1.)

(P2) The primitive actions and predicates in S_2 are precisely those of S_1.

(P3) For every input, the sequence of primitive actions and predicates executed in S_2 is identical to that in S_1.

(P4) S_2 can be obtained from S_1 by "node splitting". (Basically, node splitting allows one to eliminate structures with multiple inputs by making multiple copies of the paths through the structures [see P1].)

(P5) Each occurrence of a primitive action or predicate in S_1 is used at most once in S_2. (i.e., multiple copies of predicates and actions in S_1 are not allowed.)

The conversion rules can now be easily stated as follows:

(a) Very Strong Conversion. A structure S_1 is said to be "very strongly" convertible to a structure S_2 iff properties (P1) through (P5) are satisfied.

"Very strong conversion" is indeed very strong. Basically, the only allowed rewriting rule in converting S_1 to S_2 is a reconfiguration of the existing predicates and actions in S_1. From a programmer's viewpoint, there is one important consideration, namely that S_1 and S_2 differ only in notational convenience.

(b) Node-Splitting Conversion: A structure S_1 is said to be "node-splitting" convertible to S_2 iff properties (P1) through (P4) are satisfied.

Node-splitting conversion is still quite strong. Basically, S_2 must be derivable from S_1 by well-defined rewriting rules (node-splitting).

(c) Strong Conversion. A structure S_1 is said to be "strongly" convertible to a structure S_2 iff properties (P1) through (P3) are satisfied.

Strong conversion is clearly not as strong as node-splitting conversion for a restructuring of the primitive actions and predicates in S_1 is allowed in S_2. Nevertheless, the reduction is still strong in the sense that the computation sequences in S_1 and S_2 must still be identical.

(d) Semantic Conversion. A structure S_1 is said to be "semantically" convertible to S_2 iff properties (P1) and (P2) hold.

Semantic conversion implies a significantly less restrictive condition than the above notions of conversion,for the only restriction on the conversion of S_1 to S_2 is the prohibition of "new semantics", i.e., new actions, predicates, or variables.

(e) Computational Conversion. A structure S_1 is said to be "computationally" convertible to S_2 iff property (P1) is satisfied.

Computational conversion is indeed weak. For the reduction of S_1 to S_2 we only require that the two structures compute the same function. The introduction of new predicates, actions, or variables are all allowed.

3.2 The Notions of Reducibility and Equivalence

The issue of "relative power" of various classes of control structures can now be precisely stated. Given a set of conversion rules, a class of structures C_1 is said to be

(a) reducible to a class C_2 (notationally $C_1 \le C_2$) if every structure in C_1 can be converted to a structure in C_2, but not necessarily vice versa.

(b) strictly reducible to a class C_2 (notationally $C_1 < C_2$) if every structure in C_1 can be converted to a structure in C_2, but not vice versa.

(c) equivalent to a class C_2 (notationally $C_1 \equiv C_2$) if every structure in C_1 can be converted to a structure in C_2 and vice versa.

Given a set of conversion rules from C_1 to C_2, reduction intuitively implies that C_1 is "less powerful" than C_2, strict reduction implies that C_1 is "strictly less powerful" than C_2, and equivalence implies that C_1 and C_2 are "equally powerful."

Given the notions of:

(a) very strong conversion
(b) node splitting conversion
(c) strong conversion
(d) semantic conversion
(e) computational conversion

we shall denote the "reduction", "strict reduction", or "equivalence" two classes of structures by

(a) $\le_{vs}$, $<_{vs}$, and $\equiv_{vs}$

(b) $\le_{ns}$, $<_{ns}$, and $\equiv_{ns}$

(c) $\le_{s}$, $<_{s}$, and $\equiv_{s}$

(d) $\le_{sem}$, $<_{sem}$, and $\equiv_{sem}$

(e) $\le_{c}$, $<_{c}$, and $\equiv_{c}$

IV RESULTS ON CONTROL STRUCTURES

This section reviews several major results on control structures and discusses their practical significance. These results fall into two main categories:

(1) The classic result of Bohm and Jacopini [B1] on the theoretical completeness of D-structures.

(2) The results of Kosaraju [K4], which place all of the control structures given earlier into a hierarchy under semantic conversion.

4.1 The Bohm and Jacopini Result

The classic result of Bohm and Jacopini on the theoretical completeness of D-structures was perhaps the first major (albeit initially little recognized) result in structured programming. This result is well-described in a paper by Mills [M1]. Briefly stated, the Bohm and Jacopini paper [B1] makes the following points:

(a) $D \equiv_c L$, i.e., any L-structure (including those permitting arbitraty transfer of control) can be converted to a computationally equivalent D-structure.

(b) In the computational conversion of an L-structure to a D-structure, boolean control variables may be introduced, but the values may be stored in a stack and only the value of the top element in the stack need be known at any given point in the program.

The importance of result (a) was the establishment that the "goto" statement is, at least theoretically, not needed to perform computations, and that three simple but familiar control structures: sequential composition, if-then-else, and while-do, are in fact theoretically complete control structures.

```
1:  if A[i] < x
        then if L[i] = 0
                then L[i] := m
                else begin L : = L[i];
                         goto 1
                     end
        else if R[i] = 0
                then R[i] := m
                else begin i := R[i]
                         goto 1
                     end;
    A[m] := x
```

Figure (6a) A control structure not reducible to a D-structure without new variables or predicates

```
v := false;
while ¬v do
      if A[i] < x
         then if L[i] = 0
                 then begin L[i] := m;
                            v := true
                      end
                 else i := L[i]
         else if R[i] = 0
                 then begin R[i] := m;
                            v := true
                      end
                 else i := R[i];
A[m] := x
```

Figure (6b) Use of a new variable to reduce the control structure of (6a) to a D-structure

An example of the conversion of an L-structure into a D-structure is given in Figure (6). This example comes from a tree searching and insertion program of Knuth [K2]. The index m denotes the array location into which a variable x is to be inserted. The arrays L and R denote the left and right branches of a tree organization that is superimposed on an array A. Figure (6a) depicts a program that contains two transfers of control back to the structure entry point. Figure (6b) shows a computationally equivalent D-structure. The conversion employs an intermediate boolean variable whose value is checked at the end of a while-do structure. Two comments are in order here. First, the D-structure of Figure (6b) is not necessarily less understandable than the L-structure of Figure (6a). Second, as we shall discuss later, the L-structure of Figure (6a) can be nicely expressed without goto's using an REC_1-control structure.

The question arises, under what conditions is a control structure semantically convertible to a D-structure, i.e. without introducing new boolean variables or changing the particular semantics of a program. The answer [K4] lies in the detection of two loops with two or more distinct exits. In general, an L-structure is convertible to a D-structure under semantic conversion if and only if the structure does not contain a traceable loop with two distinct exits. If a structure contains only loops with one exit, the structure is convertible to a D-structure.

For example, consider the program schema of Figure (7), taken from a program in Gross and Brainerd [G1]. This is a typical structure that cannot be converted to a D-structure without new variables or actions. Here we have a loop consisting of the sequence $a_3p_1p_2a_4p_3a_5$ with two exits, one through a_7 and one through a_8. Note that the branch to a_6 is not an exit from this loop since the flow of control must return to a_3. Similar arguments hold for the structure of Figure (6a).

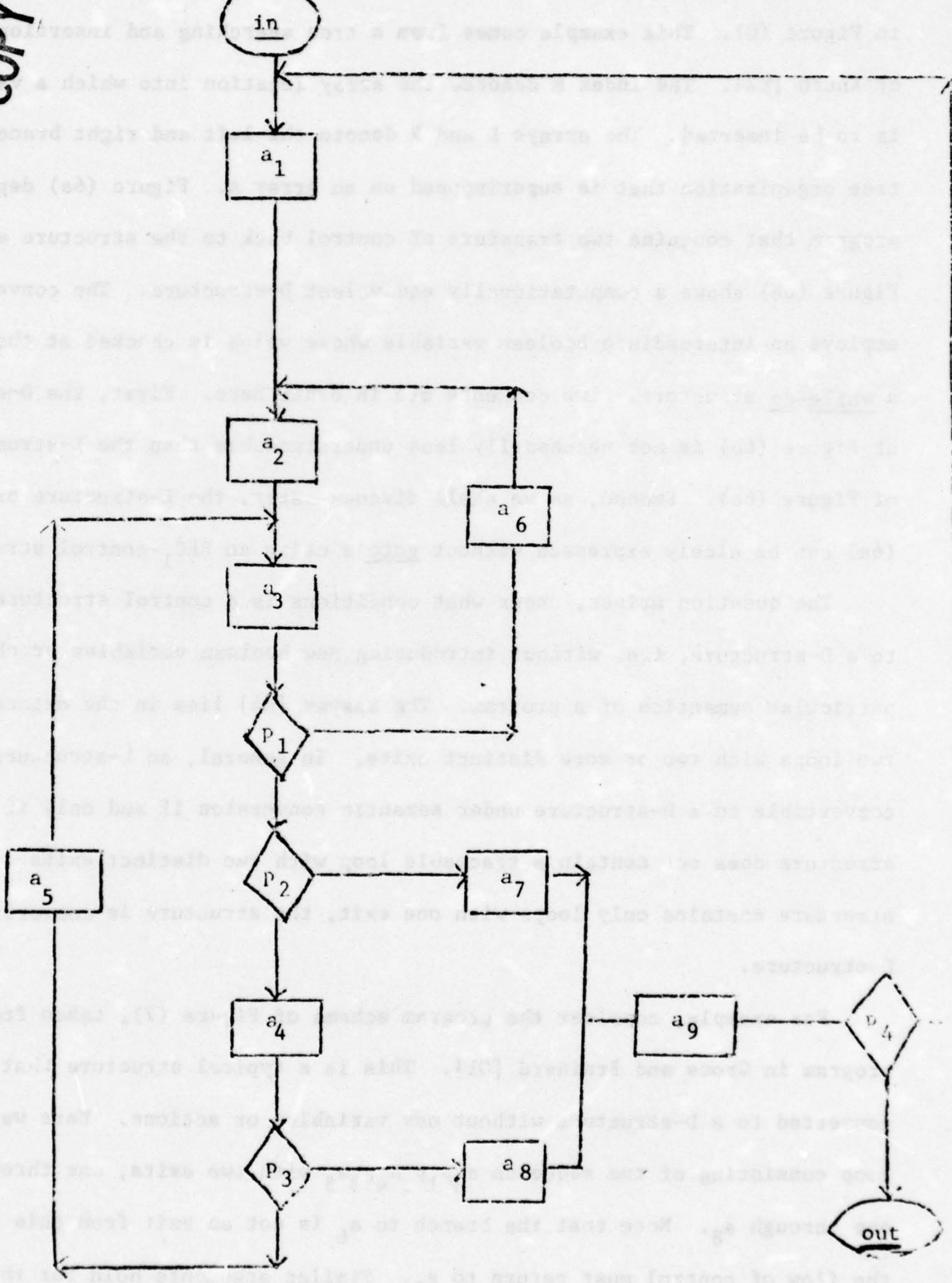

Figure (7) A "typical" structure that is not convertible to a D-structure without new variables or new actions

4.2 Kosaraju's Hierarchy of Control Structures

There have been numerous attempts to discover the limitations of D-structures as well as to explore the expressive power of other control structures. Knuth and Floyd [K3] have shown that D $<_{vs}$ L and given some intuitive ideas that D $<_{ns}$ L. Bruno and Steiglitz [B2] have formally proved that D $<_s$ L. Kosaraju [K4] and Peterson et al [P1] have proved that D $<_{sem}$ L. These results point to the fact that there are indeed fully labeled programs that cannot be converted to D-structure form without changing the length, execution time, or primitives of a given program. Peterson et al have also shown similar results for RE_n structures, i.e. $RE_1 <_{ns}$ L, and $RE_\infty \equiv_{ns}$ L.

These results fail to answer one important question, namely how do the structures given earlier relate to each other. The results of Koraraju [K4] resolve this question.

The basic results of Koraraju are outlined in Figure (8). [ref [K4] and private communication]. An upwards solid line connecting one class of structures C_1 to another class C_2 means that C_1 is strictly reducible to C_2 under the notion of semantic conversion, i.e., $C_1 <_{sem} C_2$. An upwards dotted line means that $C_1 \leq_{sem} C_2$. The main results defined in Figure 9 are summarized as follows. Under the notion of semantic conversion,

(1) for m<n, there exist BJ_n-structures which cannot be converted to BJ_m-structures. In particular, without the introduction of new predicates or actions, BJ_2-structures are"more powerful"than BJ_1-structures, which are identical to D-structures.

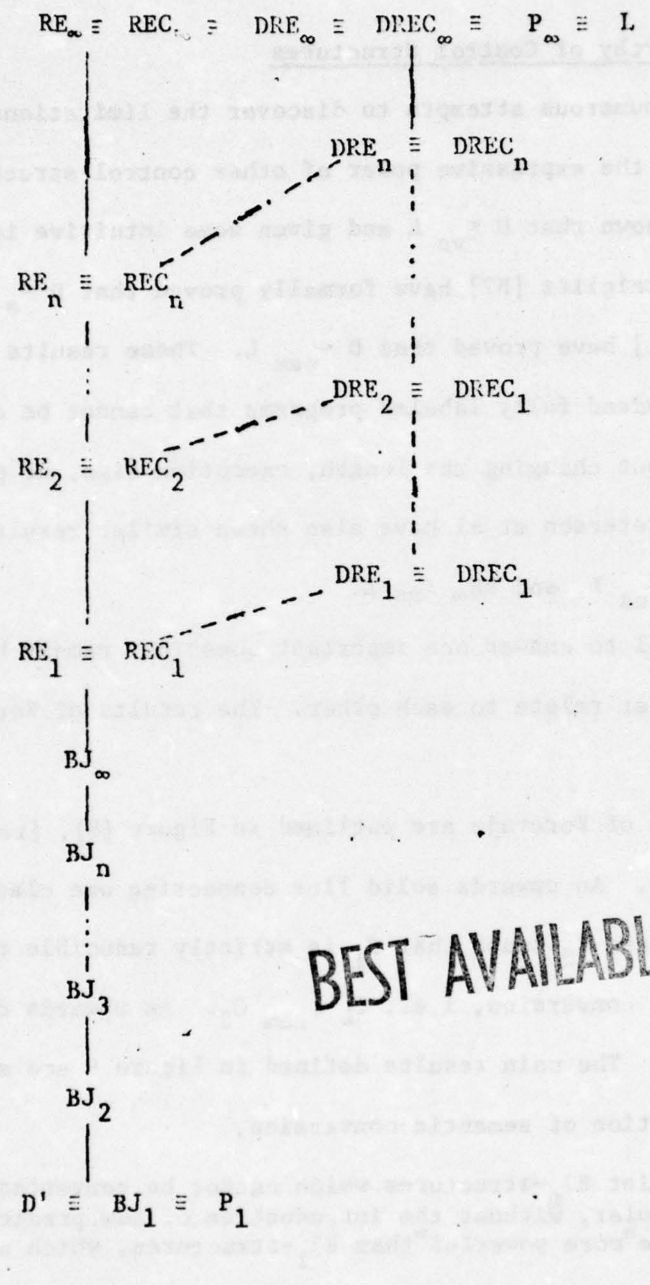

Figure (8) Kosaraju's Hierarchy of Control Structures under "Semantic" conversion.

(2) RE_n-structures are "more powerful" than BJ_n-structures or D-structures.

(3) It is believed that RE_n-structures are equivalent to REC_n-structures (as yet, this is an unproven conjecture). Somewhat surprisingly, it is believed the addition of the cycle(i) command does not add theoretical power to the repeat-exit control structure under semantic conversion.

(4) DRE_n-structures are more powerful than RE_n-structures. Again somewhat surprisingly, the addition of a while-do control structure does in fact add theoretical power to the RE_n-control structure.

(5) Finally, if no a priori bound is placed on the index n, any fully labelled structure is semantically convertible to an RE_n, REC_n, or DRE_n structure

Other results not shown in Figure (8) are given in [K4].

As an example illustrating this hierarchy, consider the structure of Figure (9 a), which is based on the control structure recently proposed by Zahn [Z1, K2]. This control structure represents a computation where a computation sequence is to be repeated until one of a number of "events" occurs. Upon realization of one of the events, the repeated loop is exited. Termination of the loop then invokes a specific computation determined by the event that has actually occurred. This control situation is a fairly natural one, and is quite close to a BJ_n-structure.

Noting that $D <_{sem} BJ_n$, the conversion of this structure to a D-structure requires a new variable, as shown by the program in Figure (9 b). On the other, hand, noting that $BJ_n <_{sem} RE_1$, this structure, can be nicely converted to an RE_1-structure, which is given in Figure (9c).

As another example of the utility of RE_1-structure, consider the tree searching and insertion of the program of Figure 6. This program can be readily converted to an RE_1-structure, as shown in Figure (10).

From a programmer's viewpoint, the results given above suggest that there is some question over the practical utility of programming with only D or D'-structures. Aside from questions of efficiency, the examples also suggest that the use of stronger control structures like RE-structures and their variants may obviate the need for goto's. In the next section I present a key example that, in fact, presents evidence counter to these suggestions.

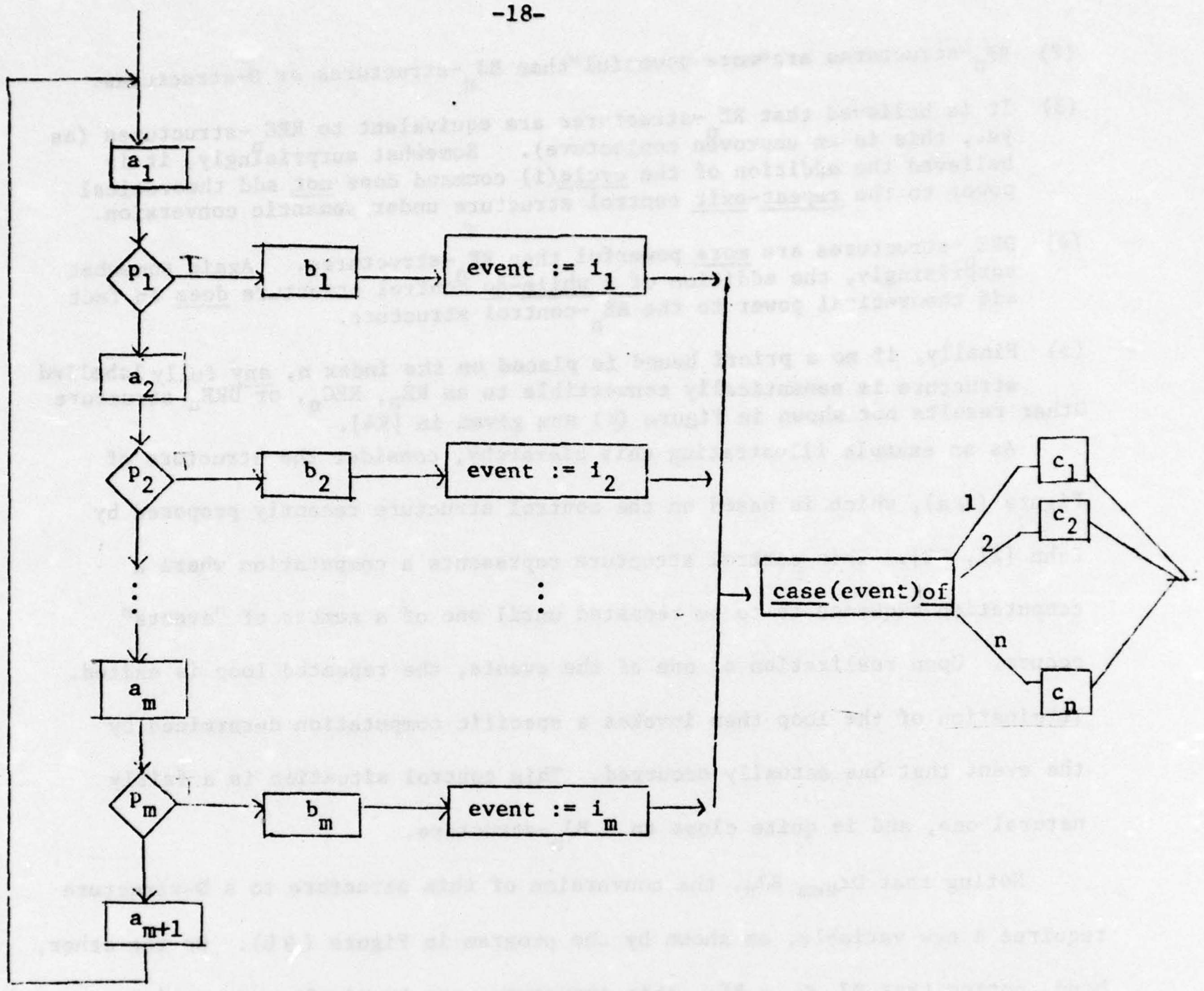

Figure (9a) <u>The Control Structure proposed by Zahn</u>

$1 \le i_1, i_2, \ldots, i_m \le n$

```
v  := false
while ¬ v do
begir
        v  := true;
        a_1
        if p_1
        then begin b_1;
                   event  := i_1
             end
        else begin
             a_2
             if p_2
             then begin b_2;
                        event  := i_2
                  end
             else
                       .
                       .
                       .
                       begin
                       a_m;
                       if p_m
                      then begin b_m;
                                 event  := i_m
                           end
                      else begin
                           a_m+1;
                           v  := false
                           end
                       end


     end ;
     case (event) of
          1:  c_1;
          2:  c_2;

          n:  c_n
     end
```

Figure (9b) Zahn's Control Structure expressed as a D-structure (under computational conversion)

```
repeat $a_1$;
       if $p_1$ then begin $b_1$;
                           event := $i_1$;
                           exit (1)
                     end;
       $a_2$;
       if $p_2$ then begin $b_2$;
                           event := $i_2$;
                           exit (1)
                     end;
       :
       $a_m$;
       if $p_m$ then begin $b_m$;
                           event := $i_m$;
                           exit (1)
                     end;
       $a_{m+1}$
end


case (event) of
     1: $c_1$;
     2: $c_2$;
     :
     n: $c_n$
end
```

Figure (9 c) Zahn's Control Structure expressed as an RE_1 -structure

```
repeat
      if A[i] < x
         then if L[i] = 0
                 then begin L[i] := m;
                            exit (1)
                      end
                 else i := L[i]
         else if R[i] = 0
                 then begin R[i] := m;
                            exit (1)
                      end
                 else i := R[i]
end;

A[m] := x
```

Figure (10) Tree-search program of Figure (6) as an RE_1-Structure

V. AN EXAMPLE

When all is said and done, the practicing programmer is primarily interested in solving problems using some given set of control structures. Theorems and results on the conversion of one program or flowchart into another form may be of some interest, but certainly not the basic issue. This section presents an example directed at resolving this important issue. In particular, are there problems for which D or D'-structures do not provide as clear a solution as REC_n-structures. More precisely, are there problems for which there is a solution $S_2 \in REC_2$ and for any reasonable solution $S_1 \in D$, $S_1 \equiv_c S_2$ and S_2 is significantly clear than S_1?

I must admit, the problem presented here was originally proposed with the hope of supporting a positive answer to the above question. The problem appeared to have the right set of ingredients, i.e. the need for cycling back to a loop entry from within a loop and the need for an escape exit nested within multiple loops.

This problem is called the "qualified name" problem. Basically, the problem is to write a program segment to set the value of a variable LEGAL_NAME to true or false according to whether a given PL/I qualified name is a legal or illegal reference. In PL/I, one can declare "structures" with nested components, e.g.

```
DECLARE  1 A,                      DECLARE 1 X,
           2 B,                              2 B,
             3 C CHAR(5),                      3 C FLOAT,
             3 D FIXED;                        3 E FLOAT;
```

A "reference" to a structure is considered legal if and only if the reference refers to one and only one declared structure component. Using the above declarations, A, A.B, A.B.C, and B.E are legal references, whereas B and B.C are illegal.

To solve this problem, a number of primitives are assumed:

(a) A linked list of entries call QUALIFIED_NAME, which represents the information about a qualified name.

(b) A function BASE_ENTRY, which when applied to a qualified name yields the base entry in the list. e.g. the base entry in the qualified name A.B.C is the entry for C.

(c) A linked list of entries called SYMBOL_TABLE, which contains entries for each identifier declared in a program.

(d) A function NEXT, which when applied to a null symbol table entry gives the first entry, and which when applied to a non-null symbol table entry gives the next entry in the symbol table (assuming some predetermined order).

(e) A function FATHER, which when applied to a qualified name entry or symbol table entry, yields the next higher-order entry in the corresponding qualified name or symbol table, or the null entry if there is no father entry. For example, in the linked list for A.B.C, the father of the entry for C is the entry for B, and the father of the entry for A is the null entry.

(f) A function NAME, which when applied to a qualified name entry or a symbol table entry yields the identifier for that entry.

A solution to this problem using REC_2-structures is given in Figure (11a). Here, the PASCAL case statement is extended to allow for multiple case conditions. This solution is quite clear and makes liberal use of cycles and exits. The conversion of this solution to a D or D'-structure under restricted conditions (e.g. any of the properties P2 through P5) is highly tedious exercise, resulting in a much longer and less efficient solution. Nevertheless, a new (computationally equivalent) solution using D-structures can be devised, as given in Figure (11b). This solution compares quite favorably with the solution using REC_2-structures.

It is important to comment here that, in addition to the formal results presented earlier, that there have been numerous other papers [F1,L1,P1,W4,Z1] suggesting the limitations of D or D'-structures. As far as I can perceive, most of these papers only compare the conversion of abstracted program schemas or flowcharts into D or D'-structure form. Not once have I seen a problem that really shows the limitations on clarity with D or D'-structures. The classic case of the abnormal exit from some deeply rested procedure just does not hold weight, for the notion of passing control to a procedure that does not return control to the <u>calling</u> program segment is counter to the very notion of 1-in, 1-out control structures.

I have long supported the view that D and D'structures are not sufficient for the practicing programmer. Recently I have tried to support this opinion with example problems far too numerous to mention here. Frankly, I have not found such an example problem.

```
QN_ENTRY              :=  BASE_ENTRY(QUALIFIED_NAME);
BASE_ID               :=  NAME(QN_ENTRY);
ST_ENTRY              :=  NULL;
DIRECT_HIT            :=  false
NUM_PARTIAL_HITS      :=  0;

repeat

      ST_ENTRY := NEXT(ST_ENTRY);

      case  (ST_ENTRY=NULL, NAME(ST_ENTRY)=BASE_ID) of

            (T,F):  exit (1)

            (F,F):  cycle (1)

            (T,T):  {cannot occur}

            (F,T):  begin
                       LOCAL_QN_ENTRY := FATHER(QN_ENTRY);
                       LOCAL_ST_ENTRY := FATHER(ST_ENTRY);
                       SKIP           := false;

                       repeat

                             case (LOCAL_QN_ENTRY=NULL, LOCAL_ST_ENTRY=NULL) of

                                 (T,T):  if SKIP
                                            then NUM_PARTIAL_HITS := NUM_PARTIAL_HITS + 1
                                            else begin DIRECT_HIT := true;
                                                       exit(2)
                                                 end

                                 (T,F):  NUM_PARTIAL_HITS := NUM_PARTIAL_HITS + 1

                                 (F,T):  {no operation}

                                 (F,F):  begin
                                               if NAME (LOCAL_QN_ENTRY)=NAME(LOCAL_ST_ENTRY)
                                                  then LOCAL_QN_ENTRY := FATHER(LOCAL_QN_ENTRY)
                                                  else SKIP := true;
                                               LOCAL_ST_ENTRY := FATHER(LOCAL_ST_ENTRY);
                                               cycle(1)
                                         end
                             end {case};

                             cycle(2)

                       end {repeat}
                    end
      end {case}

end;

if DIRECT_HIT ∨ (NUM_PARTIAL_HITS=1)
      then LEGAL_NAME   := true
      else LEGAL_NAME   := false
```

Figure (11a) A Solution to the Qualified Name Problem as an REC_2-Structure

```
QN_ENTRY            :=  BASE_ENTRY(QUALIFIED_NAME);
BASE_ID             :=  NAME(QN_ENTRY);
ST_ENTRY            :=  NEXT(NULL)
DIRECT_HIT          :=  false;
NUM_PARTIAL_HITS    :=  0;

while  (ST_ENTRY ≠ NULL) ∧ ( DIRECT_HIT)  do
begin

     if  NAME (ST_ENTRY) = BASE_ID

          then begin

                 LOCAL_QN_ENTRY:= FATHER (QN_ENTRY);
                 LOCAL_ST_ENTRY:= FATHER (ST_ENTRY);
                 SKIP  := false;

                 while  (LOCAL_QN_ENTRY ≠ NULL) ∧ (LOCAL_ST_ENTRY ≠ NULL) do
                   begin
                        if NAME(LOCAL_QN_ENTRY) := NAME(LOCAL_ST_ENTRY)
                           then LOCAL_QN_ENTRY:= FATHER(LOCAL_QN_ENTRY)
                           else SKIP           := true;
                        LOCAL_ST_ENTRY         := FATHER(LOCAL_ST_ENTRY);
                   end;

                 case (LOCAL_QN_ENTRY = NULL, LOCAL_ST_ENTRY = NULL) of

                        (T,T): if SKIP
                                  then NUM_PARTIAL_HITS := NUM_PARTIAL_HITS + 1
                                  else DIRECT_HIT       := true

                        (T,F): NUM_PARTIAL_HITS := NUM_PARTIAL_HITS + 1

                        (F,T): {no operation}

                        (F,F): {cannot occur}

                 end {case}

               end {begin};


     ST_ENTRY := NEXT (ST_ENTRY)

   end;

   if DIRECT_HIT ∨ (NUM_PARTIAL_HITS =1)
      then LEGAL_NAME := true
      else LEGAL_NAME := false
```

Figure (11b) A Solution to the Qualified Name Problem as a D'-Structure

VI. CONCLUSIONS

There are three basic conclusions of this paper.

(1) From a programmer's viewpoint, results relating to the conversion of one program form to another form under restricted conversion rules are mainly of theoretical interest only.

(2) The utility of the goto, as well as other higher (non D or D') control structures, is seriously questioned.

(3) The utility of D and D'-structures is supported.

My first conclusion may be difficult to accept, for there have been numerous formal results (presented here and elsewhere) on the limitations of control structures under various notions of conversion. It is tempting to conclude from these results that the practicing programmer would be unduly limited with the control structures that did not hold up well under conversion. As mentioned earlier, the practicing programmer is hardly ever concerned with converting programs from one form into another. My contention is that formal results on conversion provide little real support for the practical use of any particular control structure.

My second conclusion agrees with the views of Mills [M1] and others. I have found no evidence for retaining the goto statement. The recent work of Knuth [K2] surveys many opinions on the use of various control structures, including the goto, However, I strongly believe the arguments that he advances in favor of the goto, clarity and efficiency, are not supported.

The argument from clarity is exemplified by "Sometimes it is necessary to exit from several levels ... and the most graceful way to do this is a direct approach via the goto or its equivalent." [K2, p. 18] Knuth discusses eight example problems and points out the virtues of several solutions that use the goto. In my opinion, not one of these solutions is clearer than the solutions without the goto statements. Consider, for example, the programs in Figures (6a) and (6b) which were derived from the "tree searching" examples of Knuth. The solution using the goto statement (6a) is not obviously clearer than the D-structure one in (6b). Furthermore, changing the name of the boolean variable "v" to a more descriptive one, e.g. "empty space found", makes the debate almost vacuous. Clarity is, of course, a highly subjective quality, but I believe that a thoughtful reading of these examples will support my contention.

The argument from efficiency, that the goto is less time consuming than alternative control structures, is frequently made. Knuth, for example, says "Sooner or later people are going to find that their beautifully structured programs are running at only half speed...[K2, p. 3] He does present several example programs where a solution with goto statements is indeed more efficient than solutions with alternative control structures (though a factor of two is never obtained). Nevertheless, it is my basic contention that all such example programs would be just as efficient if processed by a good optimizing compiler. Certainly, no optimizing compiler can be expected to perform "macro-efficient" optimizations like the conversion of a linear search into a binary one. On the other hand, redundant tests and repeated actions are typical of the "micro-efficient" conditions that can be eliminated by good optimizing compilers, rare though they may be. This latter type of optimization should not be the responsibility of the typical programmer, who should be primarily interested in developing clear, macro-efficient programs.

Similarly, the same clarity and efficiency arguments do not support to any great degree the multiple-exit control structures, like that proposed by Zahn [Z1, K2]. Furthermore, these structures do not appear to provide a more "natural" way of thinking about the problem.

My third conclusion relates to the utility of D'-structures over D-structures. Readers may have observed the use of case, if-then, and repeat-until structures (all of which are D'-structures) in the solution to the qualified name problem. From the results presented earlier, the only real differences between D and D'-structures is notational convenience. For example, the use of case structures can often prevent the need for multiple nested if-then-else structures, and the use of repeat-until structures can often prevent the use of somewhat artificial while-do structures. Since D'-structures preserve the important 1-in, 1-out property of D-structures, the notational convenience provided by D'-structures is strongly recommended.

In parting, I must admit that any recommendation for a good set of control structures is indeed subjective. However, I must conclude from this examination that considerable new and definitive evidence is needed before we suggest that D or D' control structures, with all their clarity and simplicity, are not sufficient for the practicing programmer.

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